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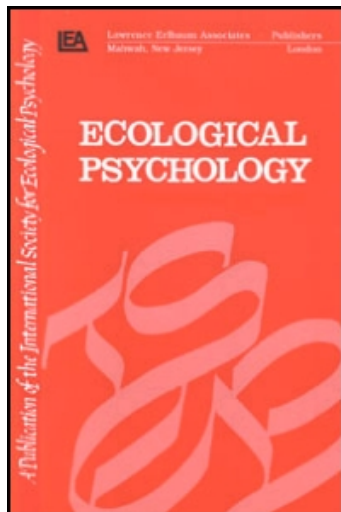
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Transfer of Calibration Between Length and Sweet-Spot Perception by Dynamic Touch

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Calibration is the process that scales perceptual judgment or action to information. An earlier study (Withagen & Michaels, 2004) suggested that perceptual calibration is specific to information-to-perception relations. In the present experiments, the authors tested this hypothesis by asking whether there is transfer of calibration between the perception of the length of an unseen, wielded rod, and perception of its sweet-spot location. In two experiments, visual feedback was used to recalibrate an information–perception relation. The recalibration of length perception by dynamic touch was found to transfer to sweet-spot perception by dynamic touch. Conversely, transfer from sweet-spot perception to length perception was found in only half of the participants. The authors concluded that calibration is not confined to information–perception relations. It is suggested that the observed transfer of calibration can be accounted for in terms of feedback information.

To behave successfully, an animal's perception and action should be appropriately scaled to the environment. Calibration is the process that achieves this scaling (e.g., Adolph & Avolio, 2000; Bhalla & Proffitt, 1999; Bingham, Zaal, Robin, & Shull, 2000; Jacobs & Michaels, 2006; Mark, 1987; Pick, Rieser, Wagner, &

Garing, 1999; Redding & Wallace, 1997a; Riley & Turvey, 2001; Wagman, Shockley, Riley, & Turvey, 2001; Withagen & Michaels, 2002, 2004). We take calibration to bear on the relation between the perceptual information exploited and the subsequent perception or action. More precisely, calibration is the process that establishes and maintains the appropriate relation between the informational variable and the perception or action (e.g., Jacobs & Michaels, 2006; Withagen & Michaels, 2002, 2004). In some places, we use the term *recalibration* to emphasize a change in existing calibration values.

Calibration is required in various circumstances. First, it can be needed to compensate for a change in the action capabilities of the body when the change is not specified by the detected perceptual information. Mark (1987), for instance, suggested that the information about the sit-on-ability and the climb-on-ability is scaled to eye-height, rendering it necessary for the perceptual system to recalibrate when one is standing on blocks. Second, recalibration can be needed because a change in environmental constraints can alter the perceptual consequences of an action (e.g., Rieser, Pick, Ashmead, & Garing, 1995). For instance, changing to a car with power steering requires a rescaling of the information-to-action relation for the driving to be successful. A third, and maybe the most compelling, reason for the indispensability of the process of calibration is that perceptual-motor systems are demonstrated to drift in the absence of feedback. For instance, participants who were to reach to previously seen objects progressively lose their accuracy when visual and haptic feedback on the outcome of the reaches is absent (Bingham et al., 2000). This suggests that calibration is a continual process.

Calibration in perception-action has received considerable attention lately (e.g., Adolph & Avolio, 2000; Bhalla & Proffitt, 1999; Bingham et al., 2000; Jacobs & Michaels, 2006; Mark, 1987; Pick et al., 1999; Redding & Wallace, 1997a; Riley & Turvey, 2001; Wagman et al., 2001; Withagen & Michaels, 2002, 2004). Among the issues addressed is the organization of calibration. In the action domain, there is ample evidence that calibration can transfer (e.g., Abeele & Bock, 2002; Hamilton, 1964; Rieser et al., 1995), so the transfer of calibration may provide a window into its organization. One suggestion is that calibration in action is functionally organized, that is, the calibration of an action transfers to actions that are functionally equivalent (Rieser et al., 1995). This suggestion rests upon the principle of *motor equivalence*—an animal can generally reach the same goal in different ways involving different limbs (e.g., Hebb, 1949; Lashley, 1930). For instance, the function of moving to a place in the environment can be achieved by walking, crawling, side-stepping, walking on one's hands, and so on. To say that calibration is functionally organized is to hold that the recalibration of an action generalizes to actions that serve the same goal, regardless of whether the actions are performed by the same limbs.

Several investigations have corroborated such a functional organization of calibration in action. By letting participants walk on a treadmill that was towed by a

tractor, Rieser et al. (1995) contrived situations in which there was a discrepancy between the biomechanically specified walking speed and the optically specified walking speed. After such "rearrangement phases" the participants were to walk without vision to a seen place. Rieser et al. found that participants walked too far or not far enough, depending on the ratio of the biomechanical speed to the optical speed. This recalibration was found not only in walking but also in sidestepping, another means of locomotion. The recalibration of walking, however, did not transfer to the functionally different actions of turning in place and throwing. When, on the other hand, throwing to a place or turning in place was recalibrated, no transfer to walking was found. Berry and Rieser (1999) found further evidence for a functional organization of calibration by showing that the recalibration of turning in place by using the legs partially transferred to turning in place by using the arms. Later, Withagen and Michaels (2002) showed that the calibration of walking without vision to a seen place generalized to crawling without vision to a seen place. And Bruggeman, Pick, and Rieser (2001) found that the directional calibration of underhand throwing generalized to the direction of overhand throwing but not to walking direction. These results suggest that calibration applies to the various distinguishable ways by which a motor outcome can be achieved, regardless of the limbs involved.

Recently, we (Withagen & Michaels, 2004) tested whether there is a functional organization of calibration in the perceptual domain analogous to that claimed for action. We argued that in the perceptual domain there is a multiple realizability of functions similar to that in the action domain: An animal can, at least in some cases, detect a particular information variable in several ways involving different anatomical substrates (e.g., J. J. Gibson, 1966). A simple example of this, and the one we also exploit in the present study, is the detection of length information by dynamic touch. Humans have an impression of the length of an unseen, hand-held, wielded rod (for a summary, see Turvey, 1996). Recent studies have shown that the variable that informs about the length of the rod can be detected in multiple ways involving different anatomical substrates. For instance, the information can be detected by wielding the rod about the wrist, the elbow, the shoulder, or all of these joints (Pagano, Fitzpatrick, & Turvey, 1993). Furthermore, both the right and left hands can extract the information. Hence, the function of detecting a variable is realizable in multiple ways involving different anatomical substrates. This means that there might be a functional organization of perceptual calibration analogous to that claimed for action: The recalibration of the detection of information by one means transfers to the other means by which this function can be performed. We tested this functional organization of perceptual calibration by asking whether the recalibration of length perception with the right hand transfers to length perception with the left hand. Transfer of calibration was found, showing that calibration is not specific to the anatomical structure detecting the information. Instead, the calibration seems to be specific to the function of perceiving an environmental property by detecting

information, regardless of which anatomical structures perform this function. Thus, also in the perceptual domain does calibration appear to exhibit a functional organization.

If perceptual calibration is indeed confined to the function of perceiving an environmental property by exploiting information, then no transfer of calibration should occur from the perception of one property to the perception of some other property. In the experiments reported here, we therefore extend our analysis of the functional organization of perceptual calibration by asking whether there is transfer of calibration between the perceiving of one property to the perceiving of another property. We again use the dynamic touch paradigm. This paradigm is convenient for several reasons. First, using the dynamic touch system, one is capable of perceiving several properties of the hand-held object: length (e.g., Solomon & Turvey, 1988), heaviness (e.g., Amazeen & Turvey, 1996), center of percussion (e.g., Carello, Thuot, Anderson, & Turvey, 1999; Carello, Thuot, & Turvey, 2000), shape (Burton, Turvey, & Solomon, 1990), and width and height (e.g., Turvey, Burton, Amazeen, Butwill, & Carello, 1998). Second, dynamic touch needs to be calibrated. Earlier studies have shown that length perception of homogeneous rods is, in general, relatively but not absolutely correct. Relatedly, it has been demonstrated that the values of the calibration coefficients that would yield metrically correct length perception differ for same-sized rods made of different materials: Rods of the same length but made of materials of different densities are perceived to be of different lengths (Fitzpatrick, Carello, & Turvey, 1994; Solomon & Turvey, 1988). Thus, different calibration is needed for rods of different densities. Third, recalibration in perception by dynamic touch can be easily induced. Earlier studies showed that a few feedback trials suffice to recalibrate length perception (Withagen & Michaels, 2004) and height and width perception (Wagman et al., 2001).

PERCEPTUAL INDEPENDENCE: A PREREQUISITE

To test the hypothesis that calibration does not transfer from one information-to-perception relation to another, the to-be-compared perceived properties must each be single-valued functions of information variables, rather than coupled to each other. Lederman, Gaheshan, and Ellis (1996) have suggested that certain properties perceived by dynamic touch are not single-valued functions of informational variables but are instead based on other perceived properties. Such “percept–percept couplings” (Epstein, 1982), or interresponse couplings (e.g., Hochberg, 1974), would preclude testing the hypothesis of calibrations being specific to information-to-perception relations. After all, if perception A is based on perception B, a recalibration of B will also adjust A, but this could not count as transfer of calibration between information-to-perception relations.

Using the methods of Ashby and Townsend (1986), several investigators have demonstrated that a number of properties perceived through dynamic touch are independent of each other (see, e.g., Amazeen, 1999; Cooper, Carello, & Turvey, 1999, 2000; Stroop, Turvey, Fitzpatrick, & Carello, 2000). Among these independent properties are perceived length and the perceived center of percussion of a rod: People can perceive rods as being of the same length while being different in the locations of their centers of percussion, and they can perceive rods having the same location of the center of percussion as differing in length (Cooper et al., 1999). We chose these properties to test whether perceptual calibration is specific to information-to-perception relations. The rationale was twofold. First, earlier studies have provided ample evidence that people have definite impressions of both the length (e.g., Pagano et al., 1993; Solomon & Turvey, 1988; Turvey & Carello, 1995) and the center of percussion (Carello et al., 1999; Cooper et al., 1999) of unseen, wielded rods. A rod's center of percussion, also known as its *sweet spot*,¹ is the place on the rod at which it is best to hit an object; it produces the least initial shock to the hand. It is a physically defined distance from the hand, computed as the ratio of the second and first moments of mass distribution. Second, both the length and the center of percussion of a rod are likely to be among the environmental properties the haptic system is able to perceive (cf. Turvey, Shockley, & Carello, 1999). As J. J. Gibson (1979/1986) asserted, for an animal to survive, the primary properties it has to perceive are the action possibilities the environment affords. The length and the center of percussion of a rod are the bases of such action possibilities. The length of a rod determines the maximum distance reachable with the rod; the center of percussion is the place on the rod at which another object can best be hit. Thus, indicating length and sweet spot are fairly natural perceptual tasks.

EXPERIMENT 1

The aim of Experiment 1 was to test whether the recalibration of length perception by dynamic touch transfers to sweet-spot perception by dynamic touch. To this end, a pretest–recalibration–posttest design was used. In the test phases, the participants were to indicate the length and sweet spot of hand-held rods. In the recalibration phase, the participants received (false) visual feedback following their length estimation. To find out about whether recalibration occurred and

¹Actually, the term *sweet spot* has been used to refer to several properties. Brody (1987) distinguished three sweet spots of a tennis racket: the place at which the ball rebounds with the maximal speed (the maximum coefficient of restitution); the place at which hitting an object produces the least uncomfortable vibration to the hand and arm (the node of the first harmonic); and the place at which hitting an object produces the least initial shock to the hand and arm (the center of percussion). In this article the term *sweet spot* is used to refer to the last of these, the center of percussion.

whether it transferred to sweet-spot perception, the results of the posttest were compared with those of the pretest for both the length and sweet-spot estimations.

Method

Participants. Eight participants (4 men and 4 women) volunteered to participate; each gave their informed consent. Their ages ranged from 23 to 29 years. Six were right-handed; 2 were left-handed.

Apparatus and materials. We used the standard experimental set-up for studies of length perception by dynamic touch. The participant was seated in a chair. On the right side of the chair was an armrest that supported the participant's right forearm. On a tabletop in front of the chair was a rail with a small, yellow block attached. The block was 2 cm wide, 3.5 cm long, and 6.5 cm high. By rotating a small wheel with the left hand, participants could move this block toward or away from themselves. Between the armrest and the rail was a curtain that blocked the participant's vision so that the hand-held rod was not visible.

We used a set of 10 wooden rods ranging in length from 30 cm to 120 cm in increments of 10 cm. The rods were homogeneous and uniformly cylindrical with a diameter of 12 mm. The wood's density was .6 g/cm³. Each rod had an 11.5 cm handle, which was separated from the rod by a disk. The rationale for using homogeneous rods was as follows: To induce recalibration, one must provide feedback based on the variable that the participants exploit; feedback based on some other variable can induce a change in the exploited variable (Withagen & Michaels, 2005). Additionally, there is a debate in the dynamic touch literature regarding what variable is exploited to perceive length (e.g., Kingma, van de Langenberg, & Beek, 2004) and sweet spot (Carello et al., 1999). By using homogeneous rods of the same material and the same diameter, we can circumvent this problem of what variable to feed back on. In such a collection of rods, all likely candidate variables are perfectly confounded with each other and correlate perfectly with length. Thus, by feeding back (a proportion of) the actual length or sweet spot, we provide feedback related to all likely variables that the particular participant is exploiting.

Procedure. The experiment consisted of a pretest, a recalibration phase, and a posttest. The test phases consisted of 10 length trials and 10 sweet-spot trials. On the length trials, the participants were to position the block at the felt distance reachable with the rod, that is, such that the rod's perceived distal end would coincide with the block. On the sweet-spot trials, the block was to be positioned to be optimally hittable with the rod, that is, at the point at which the hit would result in the least initial shock to the hand. The forearm was positioned such that the wrist extended just over the edge of the armrest. The forearm was held in this position by two vertical supports that were attached to the armrest just proximal to the wrist. The rod was to be held such that the participant's thumb just touched the disk that

separated the handle from the rod. The participants were to wield the rod freely, with the exceptions that they were to maintain their forearm on the armrest and not to touch the curtain with the rod. The location of the disk was taken as the zero point for measurements of the perceived length and sweet spot.

In both the pre- and posttests, perceivers made length- and sweet-spot judgments on each of the ten rods. The rods were offered in a random order. Blocks of five length trials were alternated with blocks of five sweet-spot trials. Half of the participants started with length trials; the other half started with sweet-spot trials. To help ensure that the participants were not comparing successive rods, they were to reposition the block at either the distal or the proximal end of the rail after each trial. The participants were not informed of the material from which the rods were made or of the number of rods used.

The recalibration phase consisted of six length-perception trials with different rod lengths in the following order: 50, 100, 40, 110, 30, 120 cm. An earlier study showed that participants are, in general, calibrated differently (Withagen & Michaels, 2004). To ensure that the same degree of recalibration was induced in each of the participants, we gave feedback based on that participant's length perception in the pretest, as follows: For each participant we found the slope and the intercept of the best-fitting line relating perceived length to actual length. To induce recalibration, we fed back actual length \times (slope plus .5) plus intercept, by positioning the block at "the distance reachable."² Thus, for each participant the feedback indicated that the rods were of a lighter material than they were calibrated for. The rationale for feeding back that the rods were longer than perceived, as opposed to shorter, is that it reduces the possibility that the perceived location of the sweet spot is distal to the fed-back location of the end of the rod. The rationale for adding a constant to the slope, instead of multiplying the slope by a constant factor, is that it enables us to inform each participant about a moderate, noticeable, and credible miscalibration, regardless of the participant's initial slope. To encourage recalibration, we asked the participants to wield the rod while looking at the block. As in the test phases, the participants were to reposition the planar surface at one of the ends of the rail before each trial.

Results and Discussion

We computed regression lines of perceived length versus actual length and perceived sweet spot versus actual length for each participant for each test phase. As stated earlier, the sweet spot is physically defined as the ratio of the second and first moments of mass distribution. Due to the relationship between these moments of

²Note that this means that in almost all cases false feedback was provided. That is, the fed-back distance reachable with the rod did not correspond with the real distance reachable with the wooden rod. However, an earlier study showed that false feedback could as easily induce a recalibration of length perception by dynamic touch as could accurate feedback (Withagen & Michaels, 2004).

homogeneous rods, their sweet spots are at two-thirds of their lengths. Hence, a slope of .67 of the perceived sweet spot versus actual length regression would mean that perceived sweet spot is appropriately scaled to actual length.

In the pretest, the linear regression for the sweet-spot judgments of Participant 7 did not reach significance, $F(1, 8) = 3.82, p > .05$. Inspection of the raw data revealed no systematic relation between perceived sweet spot and actual length, rendering it impossible to compare the slopes of pretest and posttest. Hence, we excluded this participant from the further analyses. The explained variances of the regression lines of the remaining participants were quite high: The mean r^2 of the perceived length versus actual length regression was .91; the mean r^2 of the perceived sweet spot versus actual length regression was .92. Hence, both perceived length and perceived sweet spot were linear functions of actual length.

To test whether length perception was recalibrated and, if so, whether this calibration transferred to sweet-spot perception, we analyzed the intercepts and slopes of the regression lines. The intercepts indicate what the perceived length and perceived sweet spot would have been when the actual length was zero. The slopes indicate how perceived length and perceived sweet spot were scaled to the actual length. Because we induced a recalibration of slope, we expected only a change in slope, not in intercept.

The slopes averaged across participants are depicted in Figure 1 together with error bars showing the standard deviations. We performed a repeated-measures analysis of variance (ANOVA) on the slopes with condition (pretest, posttest) and

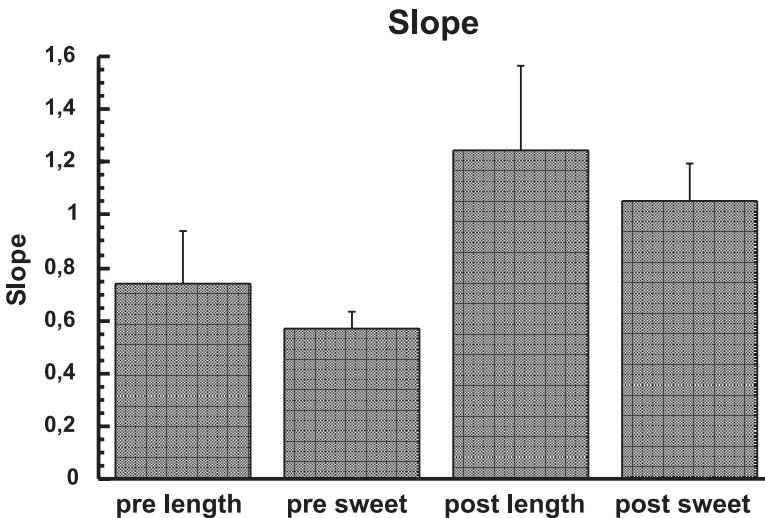


FIGURE 1 The regression line slopes averaged across participants for each test phase and each task in Experiment 1. The error bars indicate one standard deviation.

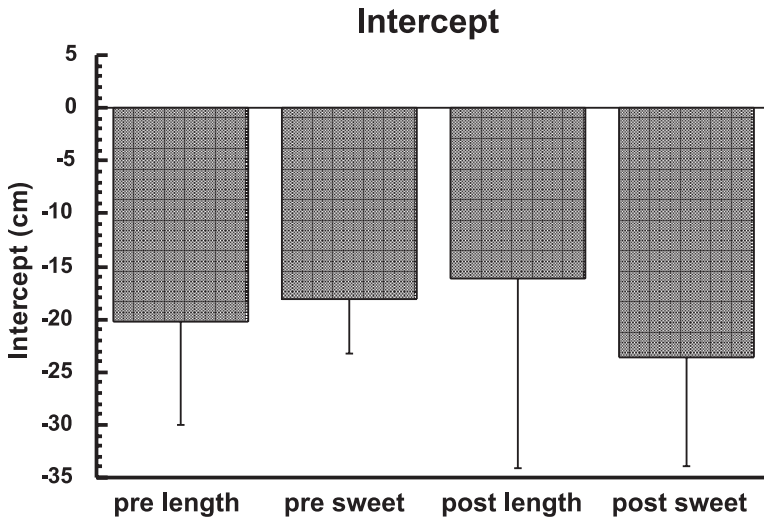


FIGURE 2 The regression line intercepts averaged across participants for each test phase and each task in Experiment 1. The error bars indicate one standard deviation.

task (length, sweet spot) as within-subject factors. Slope significantly recalibrated in keeping with the direction of the feedback, $F(1, 6) = 83.78, p < .0001$. There was a main effect of task, $F(1, 6) = 10.19, p < .05$, meaning that, as expected, there was a difference between the scaling of sweet-spot perception to actual length and the scaling of length perception to actual length. There was transfer of recalibration of slope from length perception to sweet-spot perception, as indicated by the absence of an interaction between condition and task, $F(1, 6) = .01, p > .1$. As is clear in Figure 1, the change in slope was about the same for length perception and sweet-spot perception.

The intercepts averaged across participants are depicted in Figure 2. A repeated-measures ANOVA on the intercepts with condition (pretest, posttest) and task (length, sweet spot) as within-subject factors revealed no significant effects ($ps > .05$), indicating that the intercept was not systematically recalibrated and that there was no difference between the tasks. The absence of a recalibration of intercept was in line with the feedback that the participants received, which specified only a miscalibration of slope.

Table 1 presents the regression coefficients for individual participants for each test phase and each task. These scores provide a more detailed picture of the calibration effects in both length perception and sweet-spot perception. The table shows that although there were individual differences in calibration, each participant showed considerable recalibration of slope in both the length perception and sweet-spot perception. Overall, we concluded that length perception via dy-

TABLE 1
The Slopes, Intercepts, and Explained Variances of the Regression Lines of Perceived Length Versus Actual Length,
and Perceived Sweet Spot Versus Actual Length for Each Test Phase in Experiment 1

Test Phase	Pretest						Posttest					
	Length			Sweet Spot			Length			Sweet Spot		
	Sl	In	r ²	Sl	In	r ²	Sl	In	r ²	Sl	In	r ²
1	0.75	-25.9	.96	0.51	-18.4	.93	1.35	-38.4	.98	1.10	-35.0	.97
2	0.67	-23.7	.90	0.50	-17.7	.85	0.89	3.7	.81	0.93	-23.6	.96
3	0.90	-27.0	.89	0.63	-22.6	.97	1.28	-15.0	.94	1.19	-31.5	.92
4	0.84	-28.4	.88	0.66	-21.5	.99	1.40	-37.5	.91	0.99	-29.3	.83
5	0.50	-4.4	.91	0.54	-20.0	.97	0.85	-2.6	.87	0.88	-9.9	.86
6	1.09	-12.3	.92	0.58	-8.0	.91	1.70	-6.8	.93	1.24	-12.4	.92
7	0.48	9.6	.91	0.37	13.3	.32	1.05	5.2	.97	0.76	6.7	.90
8	0.57	-8.9	.92	0.49	-10.3	.85	0.96	-3.7	.96	0.72	3.1	.94

Note. Sl = slope; In = intercept.

dynamic touch can be recalibrated by visual feedback and that this recalibration transfers to sweet-spot perception.

EXPERIMENT 2

Experiment 2 was conducted to test whether there is also transfer of calibration the other way around, that is, from sweet-spot perception by dynamic touch to length perception by dynamic touch. Again we used a pretest–recalibration–posttest design, and we used visual feedback to induce a recalibration of sweet-spot perception. To reduce the chance that the fed-back sweet spot was distal to the perceived end of the rod, we attempted to induce a decrease in the slope relating the perceived sweet spot to actual sweet spot in the recalibration phase. We reasoned that inducing a decrease in slope would be easiest if the slope in the pretest were relatively steep, which might be expected when using rods made of material with a relatively high density.³ To determine whether sweet-spot perception recalibrated and whether it transferred to length perception, the results of the posttest were again compared with those of the pretest for both the length and sweet-spot estimations.

Method

Participants, apparatus and materials. Eight new participants (6 men and 2 women) volunteered to participate and gave their informed consent. Their ages ranged from 21 to 29 years. All were right-handed. The apparatus was the same as that of Experiment 1. We used a set of 10 aluminum rods ranging in length from 10 cm to 100 cm in increments of 10 cm. The aluminum's density was 2.7 g/cm³. The rods were homogeneous and uniformly cylindrical with a diameter of 18 mm. Each rod had an 11.5 cm handle, which was separated from the rod by a disk.

Procedure. The procedure was the same as that of Experiment 1, except that the recalibration phase consisted of six sweet-spot trials using different rod lengths in the following order: 30, 60, 20, 70, 10, 80 cm. In contrast with Experiment 1, we did not use the two longest rods because their heaviness might have been fatiguing on the relatively long calibration trials. Again, we gave individual feedback based on the participant's sweet-spot perception in the pretest. For each participant, we regressed perceived sweet spot against actual length. To induce recalibration, we fed back actual length \times (slope minus .3) plus intercept. The feedback was given by repositioning the block at "the place where it is best to hit it with the hand-held rod." To further encourage the recalibration, the participants were asked to wield the rod while looking at the block.

³Carello et al. (1999) surmised that sweet-spot perception is informed by the inertia tensor, so sweet-spot perception depends on the density of the material from which the rod is made.

Results and Discussion

We computed regression lines of perceived length versus actual length and perceived sweet spot versus actual length for each participant for each test phase. The explained variances of the regressions were quite high: The mean r^2 for the perceived length versus actual length regression was .93; the mean r^2 for the perceived sweet spot versus actual length regression was .92. Thus, as in Experiment 1, both perceived length and perceived sweet spot were linear functions of actual length.

The slopes averaged across participants are depicted in Figure 3. A repeated-measures ANOVA on the slopes with condition (pretest, posttest) and task (length, sweet spot) as within-subject factors revealed a significant decrease in the slope in keeping with the direction of the feedback, $F(1, 7) = 43.05$, $p < .001$. As in Experiment 1, perceived length was scaled differently to actual length than was perceived sweet spot, $F(1, 7) = 38.62$, $p < .001$. The marginally significant interaction between condition and task, $F(1, 7) = 3.91$, $p < .1$, suggests that the recalibration of sweet-spot slope partially transferred to the length slope. Closer inspection of the results, however, showed that there were considerable individual differences in recalibration: Although all participants rescaled their sweet-spot perception, a rescaling of length perception did not occur in all the participants.

Table 2 shows that there were basically two groups of participants. The length perception of Participants 1, 2, 6, and 7 showed a recalibration effect in slope in keeping with the direction of the feedback; the length perception of Participants 3, 4, 5, and 8 did not show such an effect. In the former group, the average length

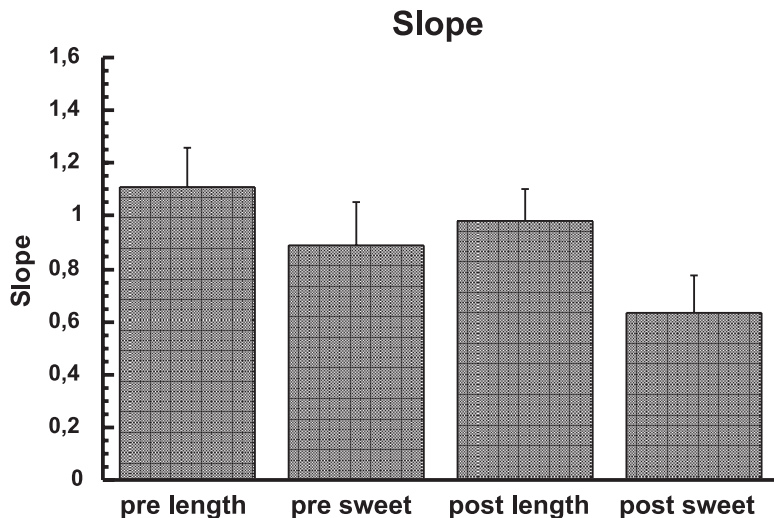


FIGURE 3 The regression line slopes averaged across participants for each test phase and each task in Experiment 2. The error bars indicate one standard deviation.

TABLE 2
The Slopes, Intercepts, and Explained Variances of the Regression Lines of Perceived Length Versus Actual Length,
and Perceived Sweet Spot Versus Actual Length for Each Test Phase in Experiment 2

Test Phase	Pretest						Posttest					
	Length			Sweet Spot			Length			Sweet Spot		
	Sl	In	r ²	Sl	In	r ²	Sl	In	r ²	Sl	In	r ²
1	1.31	-4.7	.90	0.93	-10.8	.94	0.90	-3.7	.93	0.70	-12.1	.99
2	1.15	-8.1	.89	0.86	-7.0	.85	0.93	-1.2	.89	0.64	-9.4	.83
3	0.80	-6.7	.88	0.73	-9.0	.93	0.96	1.0	.86	0.45	-4.0	.89
4	1.21	-3.6	.97	1.05	-6.6	.94	1.14	-6.8	.96	0.80	-12.9	.98
5	1.09	-10.4	.98	0.64	-10.1	.94	1.05	-18.1	.98	0.45	-14.1	.94
6	1.04	-2.9	.95	0.84	0.5	.84	0.84	7.5	.91	0.59	8.0	.80
7	1.12	-6.9	.98	1.12	-14.7	.95	0.92	-12.9	.96	0.80	-11.2	.91
8	1.17	2.5	.91	0.96	-10.1	.95	1.15	-2.3	.97	0.66	-11.4	.96

Note. Sl = slope; In = intercept.

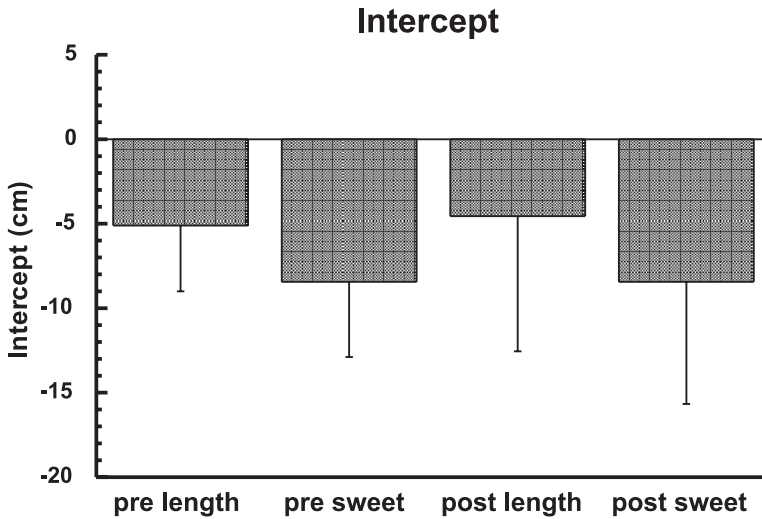


FIGURE 4 The regression line intercepts averaged across participants for each test phase and each task in Experiment 2. The error bars indicate one standard deviation.

slope changed with about the same amount as the average sweet-spot slope, analogous to what had been observed in Experiment 1. The average length slope of the latter group remained constant. Thus, it appears that the recalibration of slope transferred from sweet-spot perception to length perception in only one-half of the participants.

The intercepts averaged across participants are depicted in Figure 4 together with error bars showing the standard deviations. We did a repeated-measures ANOVA on the intercepts with condition (pretest, posttest) and task (length, sweet spot) as within-subject factors. The only effect was a marginally significant effect of task, $F(1, 7) = 5.58, p < .1$. The absence of an effect involving condition implies that recalibration of the intercept did not occur. As in Experiment 1, the absence of recalibration was in line with the feedback, which specified only a miscalibration of slope.

GENERAL DISCUSSION

In the experiments reported here, we tested whether perceptual calibration is specific to the function of perceiving an environmental property by detecting information. An earlier study suggested that perceptual calibration applies to information-to-perception relations, regardless of which anatomical structures were doing the detecting (Withagen & Michaels, 2004). Those results indicated that there is a functional organization of calibration in perception analogous to that in action as

suggested by Rieser et al. (1995). The present experiments further tested this functional specificity of perceptual calibration by asking whether there is transfer of calibration between length perception by dynamic touch and sweet-spot perception by dynamic touch. Transfer is not to be expected if perceptual calibration is specific to the function of perceiving an environmental property by detecting an information variable. In two experiments, we used (false) visual feedback to recalibrate one information-to-perception relation. We found transfer of calibration from length perception to sweet-spot perception, but we found transfer from sweet-spot perception to length perception in only one-half of the participants. The discovery of transfer of calibration leads us to conclude that perceptual calibration can apply beyond the function of perceiving an environmental property by detecting an information variable. We interpret this as evidence against a functional organization of calibration.

The remaining discussion addresses two issues. The first concerns the perceptual independence of sweet-spot perception and length perception, which this study took as its departure point. Second, we suggest a possible explanation for the observed transfer in terms of the calibration information provided by feedback.

Perceptual Independence

The rationale for our experimental design, as well as the conclusions drawn, rest to some extent upon Cooper et al.'s (1999) finding that length perception by dynamic touch and sweet-spot perception by dynamic touch are independent of each other. That is, sweet-spot perception is not based on length perception or vice versa. As argued earlier, such an independence was a prerequisite for drawing inferences about calibration. After all, perceptual dependence itself implies that recalibration can influence both perceptions, but this could not count as evidence for transfer of calibration.

One interpretation of the reported transfer of calibration between length perception and sweet-spot perception calls into question Cooper et al.'s (1999) finding of independence. That is, one might suggest that the transfer implies that the perceptions are not independent. A bidirectional dependence of length and sweet-spot perception would indeed predict simultaneous calibration. After all, if the perception of sweet spot is based on the perception of length and vice versa, a calibration of one of the perceptions yields a change in both length and sweet-spot judgments. Although the perceptual dependence suggested in the paradigm of dynamic touch is unidirectional (Lederman et al., 1996), bidirectional perceptual dependence has been observed in other paradigms (see Epstein, 1982). If such a bidirectional perceptual dependence holds for length and sweet-spot perception by dynamic touch, then the calibration of one of these perceptions indeed influences both perceptions.

However, we believe that we can eliminate this explanation. First, the present experiments are not a strong test of a bidirectional dependence of the two per-

ceived properties—other explanations of the observed effects are possible. Hence, our study cannot reject Cooper et al.'s (1999) finding of a bidirectional independence of length and sweet-spot perception. After all, their study was an explicit and strong test of perceptual dependence and demonstrated that participants could perceive rods as being of the same length, while being different in the location of their sweet-spots, and rods as having the same location of the sweet-spot, while being different in length. Second, the absence of transfer from sweet-spot perception to length perception observed in half of the participants in Experiment 2 can be seen as further evidence for Cooper et al.'s finding of independence. After all, it indicates that there is no bidirectional dependence of length and sweet-spot perception, at least not as a general rule. Third, there is another, more likely explanation of the observed transfer of calibration, an explanation to which we shall now turn.

How to Account for the Transfer of Calibration?

On the basis of the observed transfer between length perception and sweet-spot perception, we reject our initial hypothesis that perceptual calibration is specific to the function of perceiving an environmental property by detecting an information variable. The transfer illustrates that perceptual calibration can apply beyond such functions and, thus, does not follow the functional organization that we, following Rieser et al. (1995), suggested. But if calibration is not specific to functions, then how is it organized? Below we suggest a possible explanation for the transfer of calibration in terms of the calibration information that was provided by the feedback.

Although perception–action systems can drift in the absence of feedback (e.g., Bingham et al., 2000), the experimental studies to date suggest that feedback or knowledge of results is a prerequisite to the appropriate recalibration of perception. In their absence, a recalibration was not found in the visual perception of distance (E. J. Gibson & Bergman, 1954), in height and width perception by dynamic touch (Wagman et al., 2001), or in length perception by dynamic touch (Withagen & Michaels, 2004). If feedback is provided, on the other hand, a couple of trials can suffice to appropriately recalibrate perception.

Although some progress has been made in understanding the circumstances required to achieve recalibration of perception–action systems (e.g., Redding & Wallace, 1997b; Withagen & Michaels, 2005), it is not clear how best to characterize the information for recalibration: Are there different calibration-information variables that the perceiver can attend to? How is calibration information used? And what exactly does it inform about? Let us consider some possibilities. In the experiments reported here, we assumed that there were two calibration coefficients that need to be set for the perception to be metrically correct: the slope and the intercept. This means that the feedback we gave on a single trial could not inform the perceiver about the appropriate values of both calibration coefficients. Feedback on at least two trials would have been needed. So, in the experiments reported here, the information that is used to recalibrate must constitute a pattern over trials.

As to what calibration information informs about, let us consider Experiment 1 in which length was fed back. One possibility is that the calibration information just informs about the rod's length. Such information might set the calibration coefficients such that perceived length is appropriately calibrated to the information. However, if the calibration information informs only about the appropriate calibration coefficients of an information-to-perception relation, then the detection of this information ought not to yield the recalibration of both length and sweet-spot perception that we observed in each of the experiments. Another possibility, however, is that the calibration information available in the feedback informs not only about length (or in the case of Experiment 2, about sweet spot) but reflects characteristics of the set of rods as a whole, for example, the density of the material the rods are made of. As touched upon in the introduction, the nature of the information variable exploited to perceive length by dynamic touch requires different calibration coefficients for rods made of materials with different densities; the appropriate calibration coefficients for steel rods differ from those of wooden rods of the same diameter. That is, length perception by dynamic touch can be interpreted as being calibrated for homogeneous rods of some diameter made of a material with a particular density. The present experiments suggest that the same holds true for sweet-spot perception. When wooden rods were used (Experiment 1) the sweet spot was perceived closer to the hand than when aluminum rods were used (Experiment 2). Apparently, as for length perception, accurate sweet-spot judgments require different calibration coefficients for rods made of materials with different densities. This means that when multiple trials of feedback can inform the participants that the rods used had a density for which they were not calibrated, it can guide the calibration of both judgments. Such information is available in the feedback phases of each experiment: visual information about length (or sweet spot, in Experiment 2) together with the value of the haptic variable exploited informs about the type of rods used. Hence, if such information is indeed exploited by the participants to calibrate, then an adjustment of both perceived length and perceived sweet spot is likely to occur.

The above explanation for the transfer of calibration between perceiving length by dynamic touch and perceiving sweet spot by dynamic touch leaves, however, many questions unanswered. With respect to the experiments reported here, it is not clear why there was an asymmetry in transfer of calibration between the two experiments. At present, all we can do is acknowledge that multiple feedback trials provide information about several things and to raise the admittedly vague suggestion that the asymmetry might be understood in terms of differential attention to or differential exploitation of this information in different perceptual tasks.

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